Experimental Characterization of Material Properties of 3D Printed ABS

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Abstract: This study has been undertaken to examine the material properties of ABS Plastic. The 3-D printing technology named as FDM (Fused Deposition Modeling) Printing was used for fabrication of ABS component for various tests. The variety of tests such as tensile test, flexural strength test, hardness test, outgassing and CTE test were carried out examine the ABS properties. All the specimen was prepared according to relevant ASTM standards. The 45° raster angle was used to prepare the ABS component. A 3-point bending set-up was used to conduct flexural testing on test specimen. Vickers hardness set-up was used for Hardness measurement. This paper presents the FDM 3D printing process of the ABS plastic and their experimental characterization done on printed specimen to evaluate the printing parameters as well as the material properties for future applications.

***Index Terms* – ABS (Acrylonitrile-Butadiene-Styrene), FDM (Fused Deposition Modeling) printing, outgassing, CTE-Test.**

I. INTRODUCTION

The advancements in electronics and communication industry demands the need for development of newer materials and smarter manufacturing methodologies which yield better performance with the stringent size and weight limitations. Tailor made solutions involving special grade plastics with innovative non-conventional manufacturing techniques are enormously being researched for the achievement of required level of accuracy and functional properties in the electronics systems. [1]

Acrylonitrile-Butadiene-Styrene polymer, commonly known as ABS, is the work horse plastic material in automotive and aesthetics applications. Thermal resistance, light weight, easy formability, reflectivity etc. are some of the multipurpose properties of this plastic. Value added utilization of this versatile plastic in the domain of electronics and RF communication is being researched widely, to address the suitability of metalized plastics as the replacement of conventional materials on cost, weight and performance basis. 3D printing, the most popular additive manufacturing technique has opened a wide opportunity to fabricate the complex and intricate designs in the electronics and communication engineering, especially using the plastics. Among the various 3D printing technologies available, Fused Deposition Modelling (FDM) stands out due to its simplified procedures and low cost nature. FDM is commonly used for modeling, prototyping, and production applications utilizing the heated extrusion of the build material. Characterization of the properties of printed ABS parts are required to analyze and evaluate the suitability of the base material for further metalized applications in electronics and communication engineering applications.

Fused Deposition Modeling (FDM) was developed by Scott Crump, the founder of Stratasys. It was commercialized by Stratasys in 1991. FDM Process is categorized by three distinct steps: Step1: Pre-Processing (set-up and deciding the process parameters), Step2 Production (actual printing) & Step3 Post-Processing (removal of support material and surface finishing if required). [1]

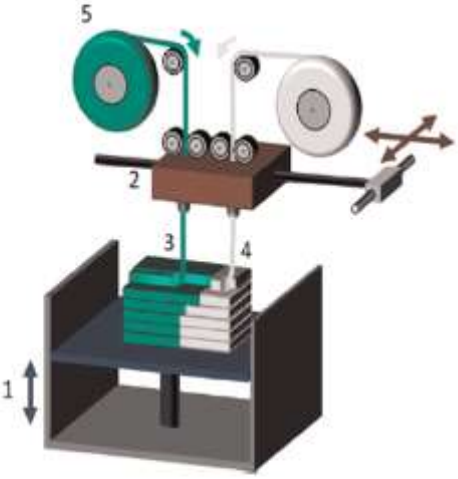


Figure 1 Schematic illustration of the FDM process
(1) Vertically movable building platform (2) horizontally movable, heated deposition unit with nozzles (3) model material (4) support material (5) feed stock of rolled material filaments.

3D printers that run on FDM technology build parts layer-by-layer by heating thermoplastic material to a semi-liquid state and extruding it according to computer-controlled paths. FDM uses two materials to execute a print job: modeling material, which constitutes the finished piece, and support material, which acts as scaffolding. Material filaments are fed from the 3D printer's material bays to the print head, which moves in X and Y coordinates, depositing material to complete each layer before the base moves down the Z axis and the next layer begins. Once the 3D printer is done building, the user breaks the support material away or dissolves it in detergent and water, and the part is ready to use. [1]

II. EXPERIMENTAL DESIGN & PROCEDURE

2.1 Development of specimen

The specimen for all the test was prepared according to their relevant ASTM standard. The tensile specimen was designed as per ASTM D-638. Here the two type of tensile specimen were prepared. The first specimen with the 100% filling density was prepared according to ASTM D-638 TYPE-IV for 3-mm thickness for tensile test which is shown in figure-2. [5]

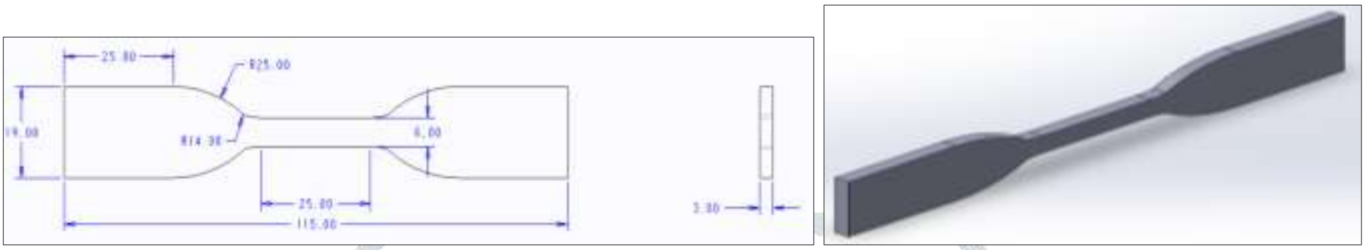


Figure 2 ASTM D638 IV (All dimension are in mm)

Second specimen for tensile test was TYPE-I specimen of ASTM D-638 for 5-mm thick plate which was partially dense (60% filling density) from inside. Which is shown in the figure-3.

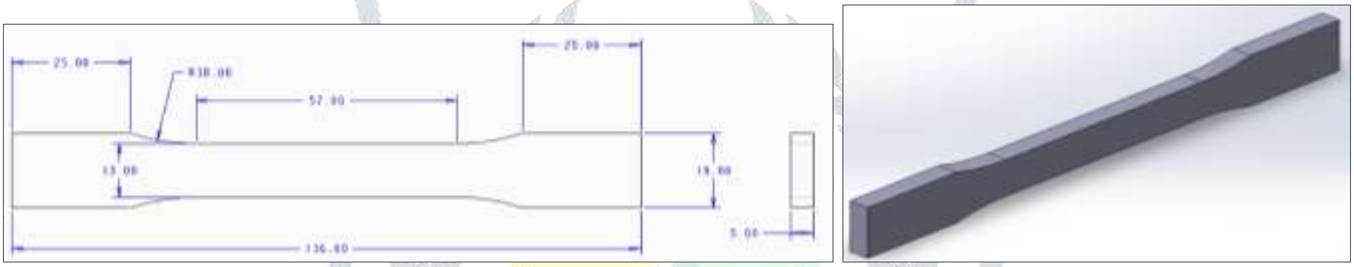


Figure 3 ASTM D638 I (All dimension are in mm)

The specimen for the flexural test was prepared according to ASTM D-790 with 100% filling density. The dimension (127mm * 12.7mm *3.2mm) of the specimen is shown in the figure 4. [6]

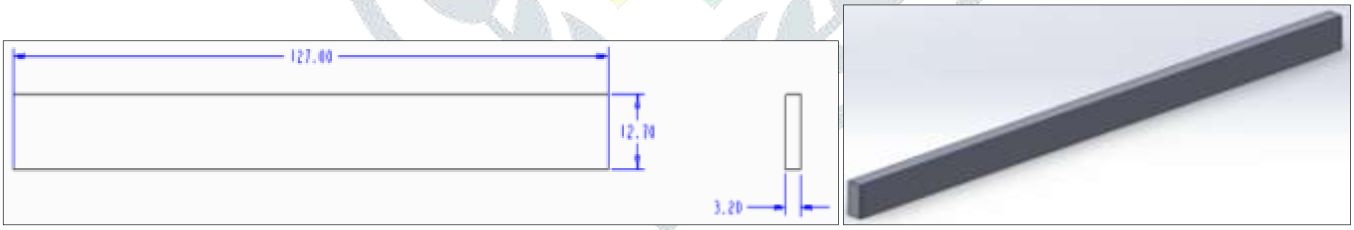


Figure 4 ASTM D-790 (All dimension are in mm)

Specimen for Outgassing test was prepared as per ASTM E595 (5mm * 5mm *5mm) with full density. Specimen for CTE test was prepared as {50mm (length) * 5mm (diameter)} with full density.

Figure 5 (a) outgassing component (b) CTE component

2.2 3D printing of specimen

3D printing of all Specimen is performed at the Rapid Prototyping Lab in COE (Center of Excellence) at LD College of Engineering, Ahmedabad. The 3D printer which is available at COE is Dimension 1200es Series. ABS material which is used to 3D print is ABS*plus*-p430 production-grade thermoplastic.

- Process parameter for FDM (Fused Deposition Modeling) printing
    1. Layer thickness = 0.01 inch (0.254mm)
    2. Orientation = 0 degree
    3. Filling configuration = 100% & 60%
    4. Nozzle diameter = 0.4mm
    5. Nozzle speed = 40 mm/s -70 mm/s

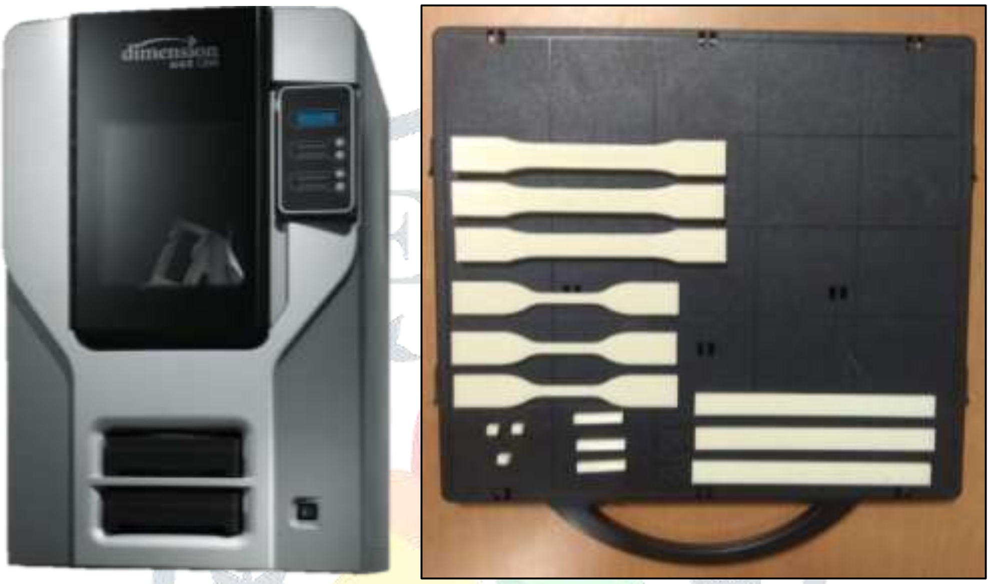


Figure 6 Dimensions SST 1200es (FDM machine) and 3D printed part

2.3 Experimental procedure

ABS material fabricated by FDM printing were characterized by 6 tests. Figure 7 shows the all tests which were performed for material characterization.

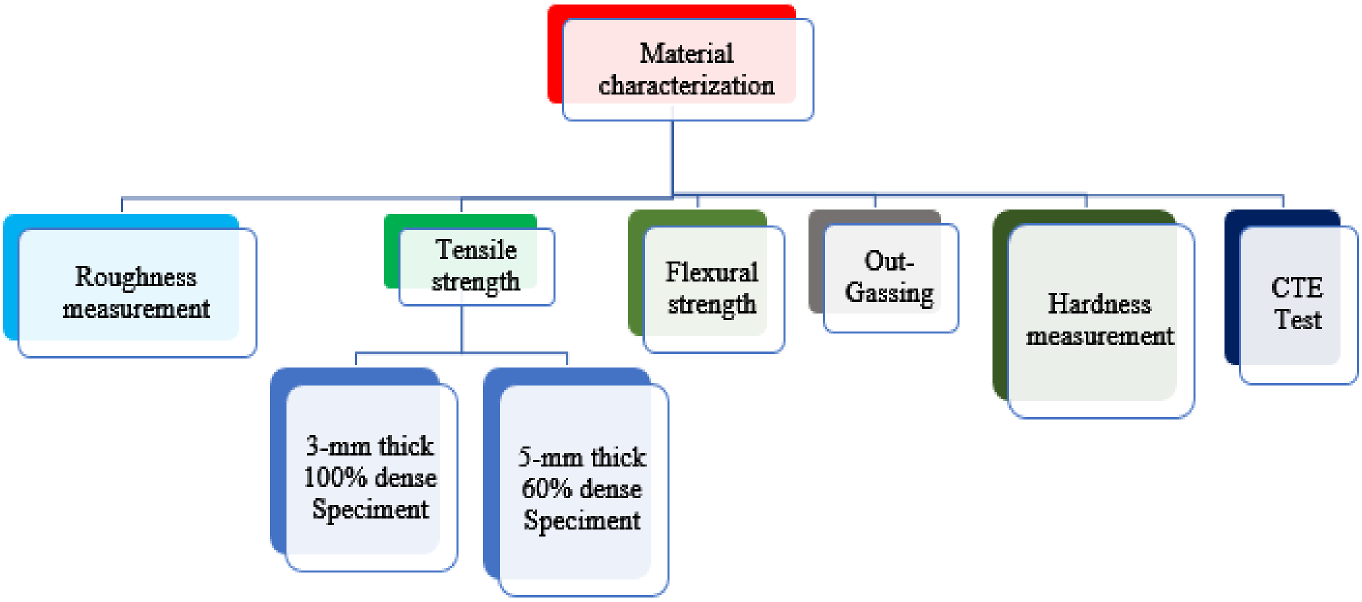


Figure 7 Material characterization

2.3.1 Roughness measurement

Roughness measurement was performed on Talysurf i-series surface measurement machine at SAC ISRO Ahmedabad. Here the value is measured at three different point on the surface in both x and y direction of the sample. The roughness value of the specimen is completely depended on the FDM process parameter such as layer resolution, orientation of part, raster width etc. The test was performed with 1mm gauge range which is clearly indicated on the cylindrical shank of the gauge.

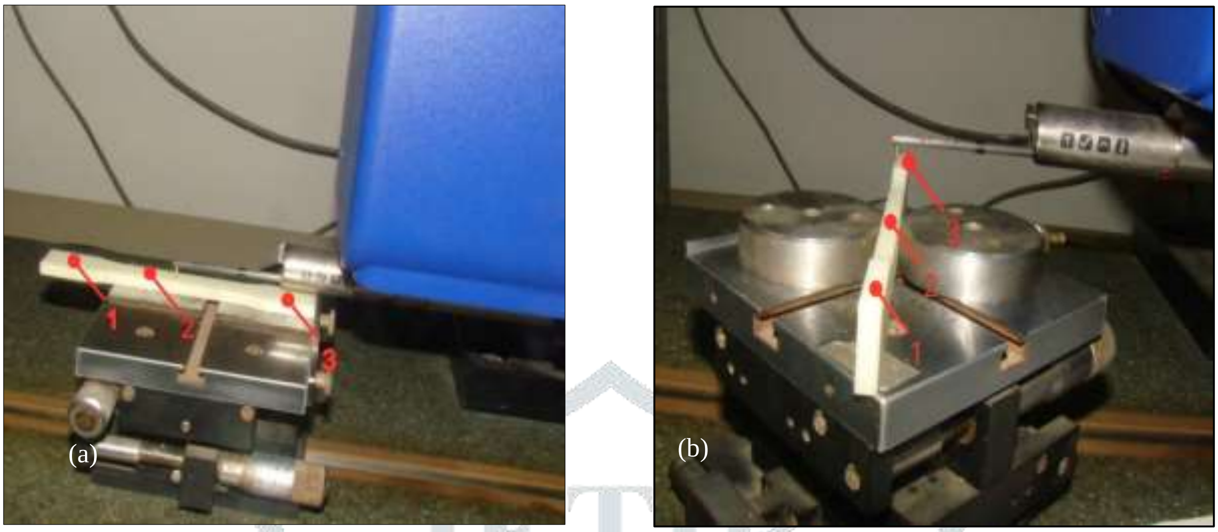


Figure 8 sample while measurement was performed (a) on horizontal surface (b) on vertical surface

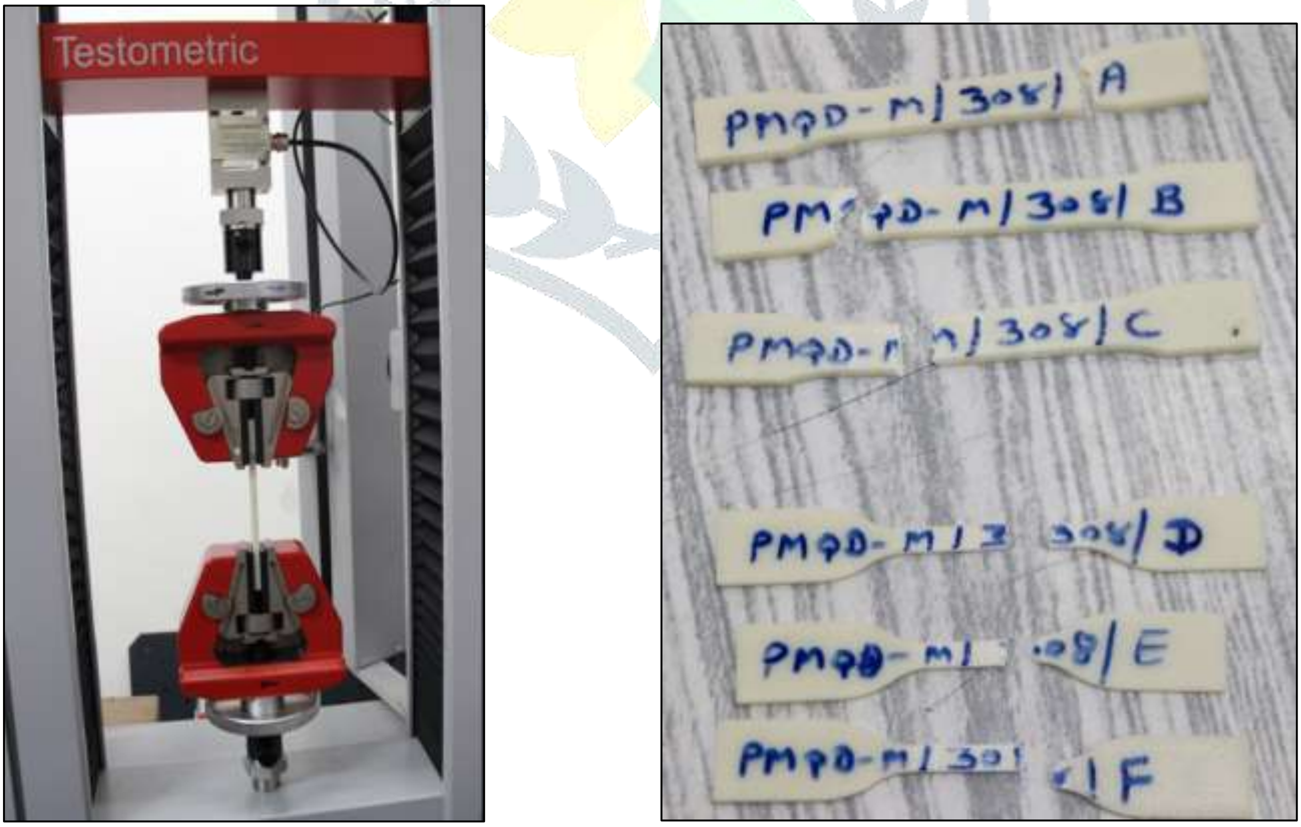
2.3.2 Tensile test

3-mm thick full dense and 5-mm thick partially dense tensile specimen was prepared as per ASTM D638.

3-mm thick full dense tensile specimen - ASTM D638 Type-IV

5-mm thick partially dense tensile specimen - ASTM D638 Type-I

Tensile test is carried out on Testometric TYPE DBBMTCL 1000KG at SAC ISRO Ahmedabad. Test is performed at 1000 kg load and 1 mm/min speed as per ASTM D638 (Standard Test Methods for Tensile Properties of Plastics). [5]



(a) (b)

Figure 9 (a) tensile test set up and (b) sample after tensile test

2.3.3 Flexural strength test

Specimen for 3-point bending test is design as per ASTM D 790 (127mm * 12.7mm *3.2mm) with full density. Test is carried out on Testometric TYPE DBBMTCL 1000KG at SAC ISRO Ahmedabad. The test is performed at 10mm/min speed as per ASTM D790 (Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials). Figure 10 shows the test fixture. [6]

Figure 10 3-point bending test set-up

2.3.4 Outgassing Test

The purpose of the outgassing test is to evaluate the mass loss of materials being subjected to 125 °C at less than 7 x 10^{-3} Pa (5 x 10^{-5} torr) for 24 hours. Here two parameters are important:

1. Total mass loss
2. Collected volatile condensable material

Total mass loss (TML): - Total mass of material outgassed from a specimen maintained at a specified constant temperature and operating pressure for a specified time. TML is calculated from the specimen mass as measured before and after test and is expressed as a percentage of specimen's initial mass. [7]

$$\mathrm{TML} = \frac{\text{Mass of test sample before test} - \text{Mass of test sample after test}}{\text{Mass of test sample before test}} \times 100\ \% \qquad (1)$$

Collected volatile condensable material (CVCM): - Quantity of outgassed matter from a test specimen that condenses on a collector maintained at a specific constant temperature for a specified time. CVCM, expressed as a percentage of specimen's initial mass, is calculated from condensate mass determined from the difference in mass of collector plates before and after test.

As per **ASTM E-595** the outgassing of ABS is performed at PMQD LAB at SAC ISRO. [7]

$$\mathrm{CVCM} = \frac{\text{Mass of collecter plate after test} - \text{Mass of collecter plate before test}}{\text{Mass of test sample}} \times 100\ \% \qquad (2)$$

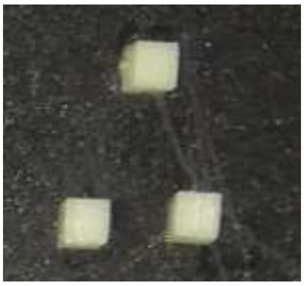


Figure 11 ABS sample for outgassing

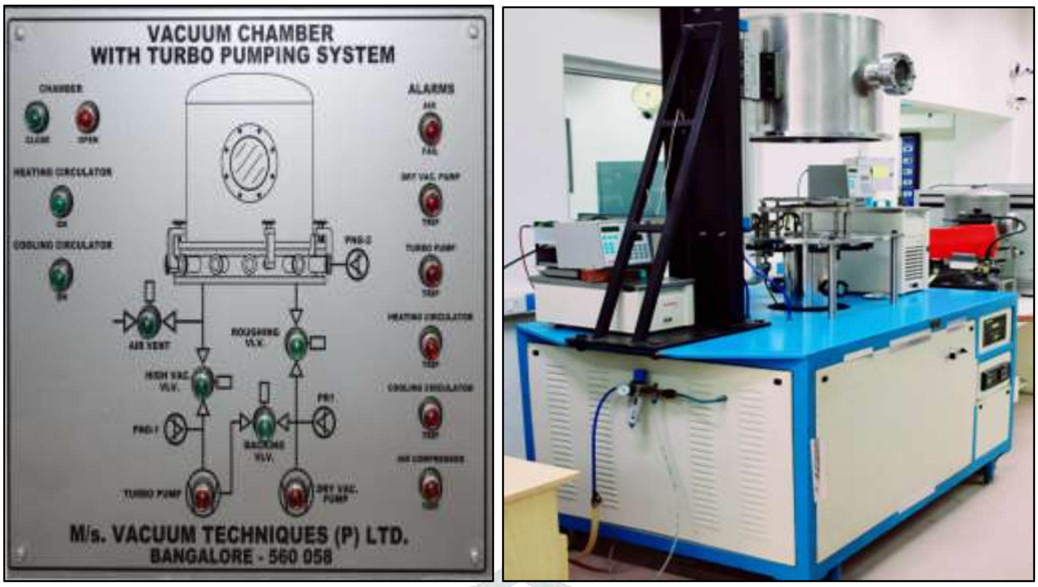


Figure 12 outgasssing test set-up

2.3.5 Hardness test

Hardness test is carried out on Vickers Hardness Tester Model: MVM – 50 PC at SAC ISRO Ahmedabad. MCS Computerized Vickers Hardness Tester is a simple and an accurate machine which loads and unloads the specimen and creates an indentation. This indentation is accurately measured by CCD camera and suitable optics. Specially developed image processing software measure the diagonal of indentation and converts it into Vickers Hardness No. Test is performed at 20 kgf load. The Viker's Hardness no. is calculated by following equation.

$$HV = \frac{2F \times \sin\frac{136^\circ}{2}}{d^2} = 1.854 \times \frac{F}{d^2} \qquad (3)$$

Where, F = Load

d= Arithmetic mean of the two diagonals, d1 & d2 in mm

This test was conducted as per ASTM D785.

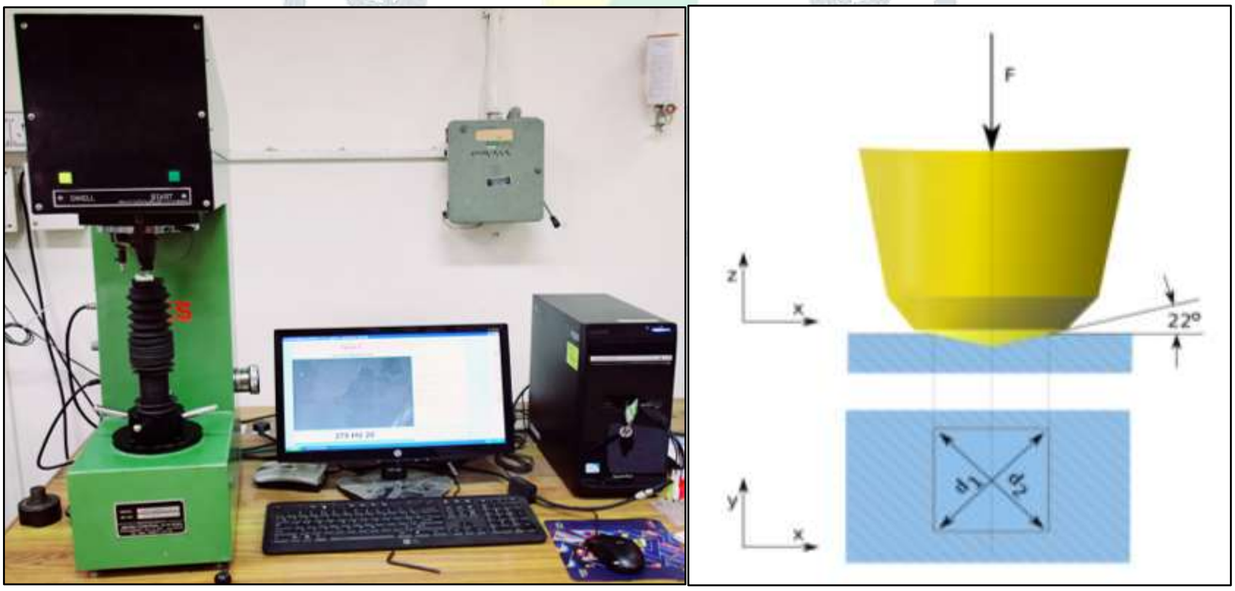


Figure 13 Hardness test set-up and Schematic of procedure

2.3.6 CTE (Co- efficient of Thermal Expansion) Test

The purpose of the CTE Test is to evaluate the change in length of materials being subjected to varying temperatures. CTE test is carried out on CTE Measurement Instrument at SAC ISRO Ahmedabad. All specification regarding the machine, procedure and parameter are enlisted in the table-1.

Table 1 CTE Test specification

Instrument Type	CTE Measurement Instrument	**Sample Types/ Sample ID / Job card/ Project**	ABS TA19006 A to C JC-19-06 R & D
Make	TA	**No. of Samples**	03
Model	DIL801	**Sample Shape Dimensions (mm)**	Cylindrical Rod Length: 50 ±0.05 Thick.: 5.0± 0.05
Operating Software	WinTA100	**Temperature Range**	-50°C to 105°C
Push Rod Type	Silica (Horizontal)	**Reference Temperature**	25°C
Applicable Standard	ASTM E 228	**Atmosphere**	Air
Technique	Dilatometry		
Method of Recording	Automatic		
Calibration Date	28.02.2019		
Calibration Standard	Aluminium Oxide		

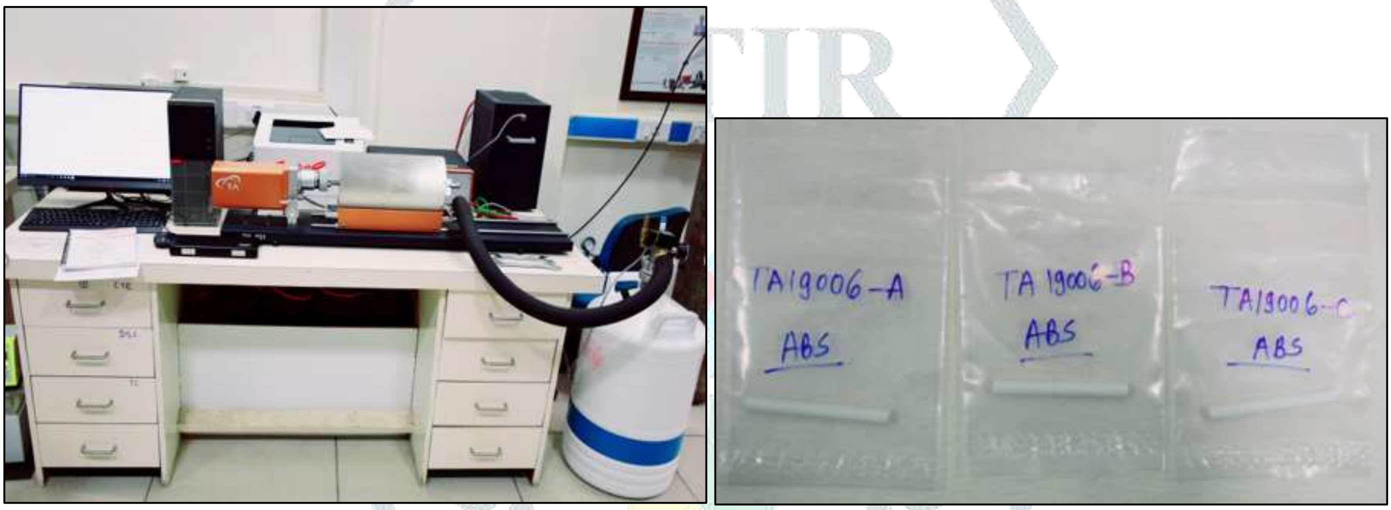


Figure 14 CTE Test Set-Up and ABS test specimen

III. RESULTS AND DISCUSSION

3.1 Roughness test result

Here the Ra value was measured at three different point on the surface in both x and y direction of the sample.

Table 2 Roughness value Ra of (a) horizontal surface (b) vertical surface

(a)

Reading No.	X-Direction (Value in µm)	Y-Direction (Value in µm)
1	8.3374	5.1665
2	6.9230	7.4382
3	7.6001	7.4327
AVG.	**7.6201**	**6.6791**

(b)

Reading No.	X-Direction (Value in µm)	Y-Direction (Value in µm)
1	1.0553	18.9194
2	2.4860	19.0755
3	3.2741	18.4749
AVG.	**2.2618**	**18.8266**

As we can see in Table 2 (a) the Ra value of horizontal surface of the specimen in x and y direction is pretty close having variation of around 1 µm. When we look at Table 2 (b) we found almost 16.6 µm gap in Ra value of the specimen in X and Y direction this was happened due to the specimen's Y- direction which is actually build direction of FDM machine. So due to poor layer resolution of FDM machine the roughness in Y direction is extremely high. If we require good surface finish in that direction than we have to reduce the layer thickness of FDM machine.

3.2 Tensile test result

All the six specimen (three specimens of 3 mm thick with 100 % filling density thickness and three specimens of 5 mm thick with 60% filling density) are tested according to ASTM D638. Force vs Elongation curve of tensile test is shown in figure 15.

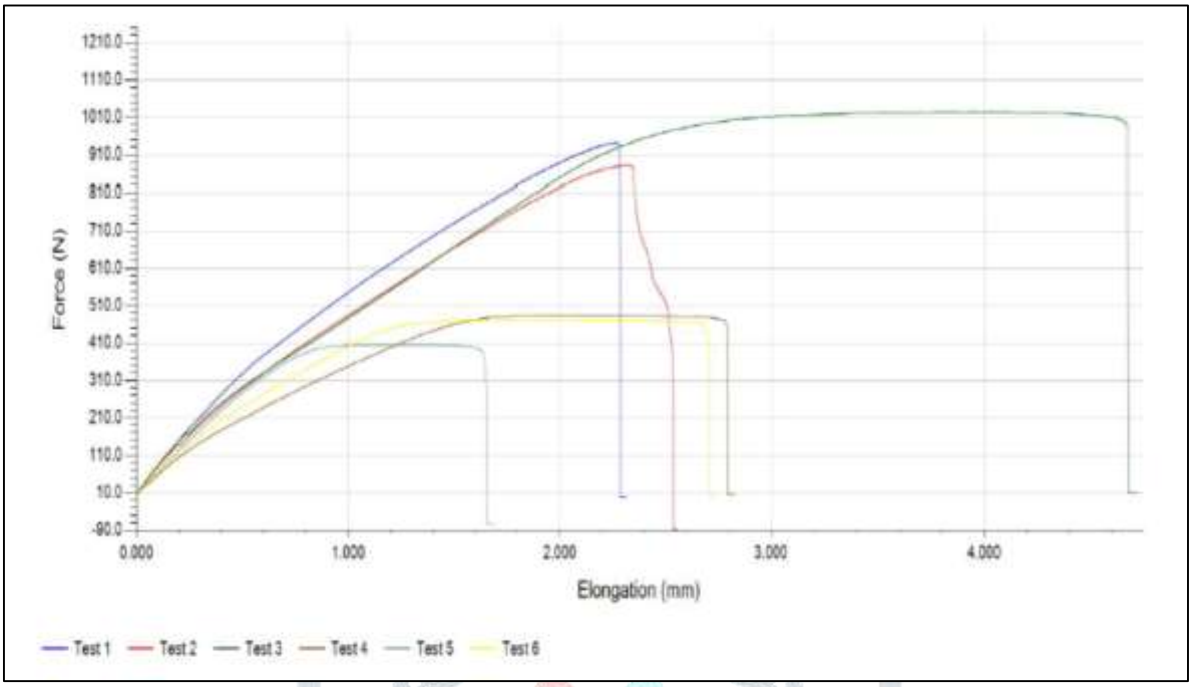


Figure 15 Force vs Elongation curve

Table 3 Detail of test specimen & Result

TEST No.	Specimen	Area (mm^2)	Youngs Modulus (MPa)	Elong. @ Yield (mm)	Force @ Peak (N)	Stress @ Yield (MPa)
1	ASTM D638 I(1)	62.5	969.577	2.266	941.665	15.066
2	ASTM D638 I(2)	62.5	816.896	2.322	882.991	14.128
3	ASTM D638 I(3)	62.5	601.962	4.027	1024.495	16.397
4	ASTM D638 IV(1)	18	2356.893	2.032	484.841	26.937
5	ASTM D638 IV(2)	18	3059.836	1.377	405.701	22.539
6	ASTM D638 IV(3)	18	2770.190	1.796	472.092	26.22

The strength (yield stress) of 3-mm thick specimen is found 25.22 MPa and the tensile elongation is 2.52%. The strength (Yield stress) of 5-mm thick specimen is found 15.19 MPa and the tensile elongation is 3.2%. Here in 5-mm thick specimen we get less strength because the filling configuration for 5 mm thick specimen is about 60%. In actual, the true area for the loading is less than 62.5 mm^2 almost 37.5 mm^2. So, with this true area strength of ABS will be 22.23 MPa. Here this value is less than the value which is listed in ABS P430 material data sheet where it is 31 MPa yield strength with 2% tensile elongation.

3.3 Flexural test result

All the three specimen with 100 % filling density were tested according to ASTM D790. Force vs deflection curve of flexural test is shown in figure 16. In this curve it can be seen clearly that ABS Specimen has sustained the 40 N load at its maximum deflection limit. The test was conduct at 10mm/min speed as per ASTM D790.

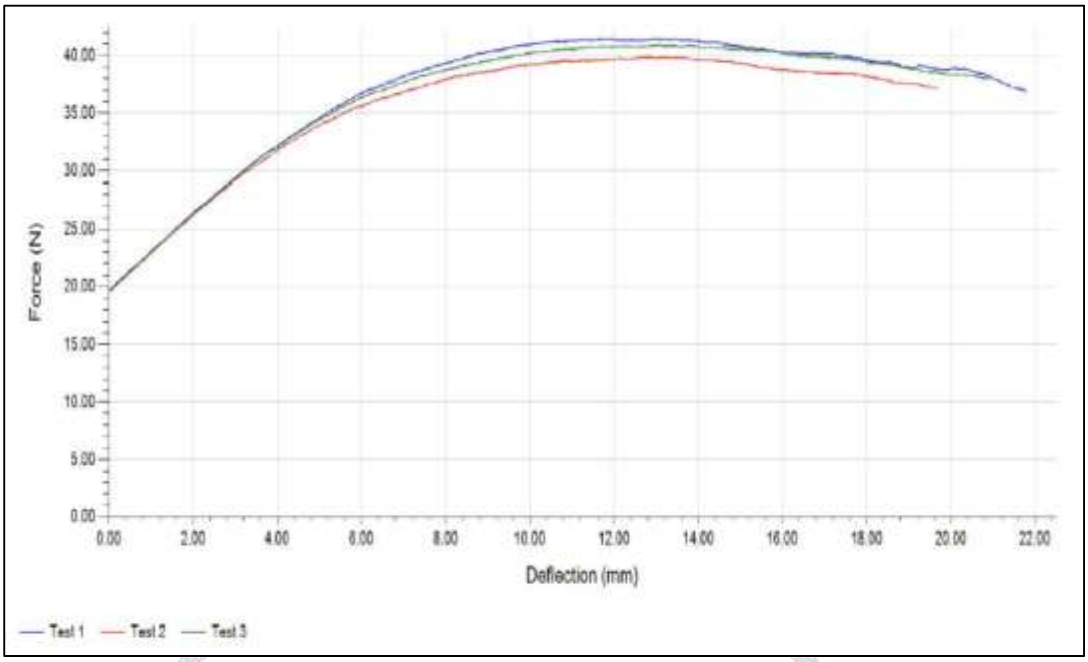


Figure 16 Force vs deflection curve of flexural test

Table 4 flexural test result

TEST No.	**Force @ Peak (N)**	**Def. @ Break (mm)**	**Bending Strength @ Peak (N/mm²)**	**Bending Modulus (N/mm²)**
1	41.5	21.785	53.205	2391.625
2	39.9	19.667	51.154	2366.89
3	41.0	20.939	52.564	2401.241
Mean	**40.8**	**20.797**	**52.308**	**2386.585**

Flexural strength of specimen is to be found 52.308 MPa and the max withstanding load is 40.8 N which is approximately near the value mentioned (58 MPa) in ABSpluse-p430 material datasheet.

3.4 Outgassing Test result

The total mass loss of ABS material during the test was found 0.00039 g which is 0.3% of initial mass (0.13 g). collected volatile condensable material was found 7.8 e-5 which is 0.06% of initial mass (0.13 g). These results meet the outgassing requirements as per ASTM E-595.

Table 5 Outgas test result

Material	% TML	%CVCM	Specified	REMARK
ABS (Acrylonitrile Butadiene Styrene)	0.3	0.06	TML ≤1% CVCM ≤0.1%	As per ASTM E-595

3.5 Harness test result

ABS specimen of tensile testing was used to measure the hardness of the ABS plastic. In figure 17 the testing procedure and the high definition image of the indentation is shown. The diagonal of the indentation was measured with the help of software and then by the help of equation 3 the HV no. measured. This test was conducted as per ASTM D785.

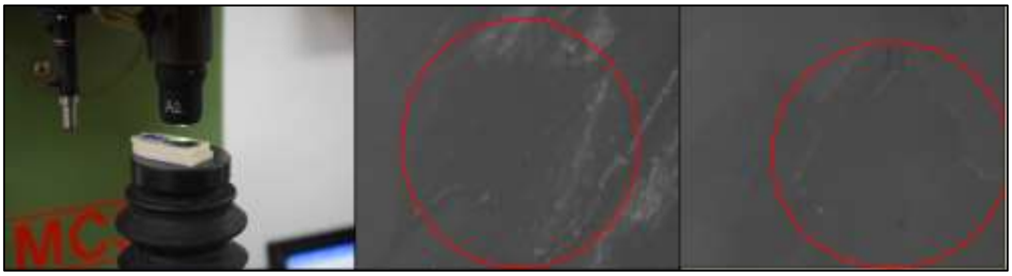


Figure 17 Hardness CCD image

Reading no.	Specimen 1	Specimen 2	Specimen 3
1(HV)	270	311	263
2(HV)	270	299	270
3(HV)	275	282	273
AVG.(HV) ≈	272	298	269

From the experiment the hardness of ABS in Vicker's hardness no. in the range of **269 – 311** HV is observed. Which is equivalent to the Rockwell no. 109.5 same as reported in ABSpluse-p430 material Datasheet.

3.6 CTE (Co- efficient of Thermal Expansion) Test result

C.T.E. Test Graphs of change in length Vs Temperature for different sample is shown in figure 18, 19 & 20.

Figure 18 ABS sample TA19006-A

Figure 19 ABS sample TA19006-B

Figure 20 ABS sample TA19006-C

Table 6 CTE Test Result

Temp. Range (°C)	**Mean Coefficient of Linear Thermal Expansion (µm/m)/°C or 10-6/K or 10-6/°C**		
	Sample 1 TA19006-A	**Sample 1 TA19006-B**	**Sample 1 TA19006-C**
-50 to 105	85.610	85.409	87.860
25 to 105	93.571	95.679	96.665
-50 to 25	77.148	74.494	78.505

From the experiment we examine the co-efficient of thermal expansion of ABS is 86.43 µm/°C which is same as reported in material datasheet.

IV. Conclusion

3D printed ABS material property were tested. From that following conclusion are observed:

i. Due to poor layer resolution of FDM machine the roughness in Y direction is extremely high (upto18 µm). If good surface finish is required in that direction than layer thickness of FDM machine has to be reduced.
ii. From tensile testing, it was determined the yield strength of ABS material is 25.22 MPa with 2.52% percentage elongation which is at best raster angle orientation condition as reported in [11]. This value is 18.5% less than the value mention in ABSpluse- p430 materiak datasheet.
iii. Flexural strength of specimen is found 52.308 MPa and the max load at which it is stand is 40.8 N which is quit near the value mentioned (58 MPa) in ABSpluse-p430 material datasheet.
iv. The ABS material is matching outgassing requirement.
v. From the experiment the hardness of ABS in Vicker's hardness no. is in the range of **269 – 311** HV. Which is equivalent to the Rockwell no. 109.5 same as reported in ABSpluse-p430 material Datasheet.
vi. ABS has lower CTE (76 µm/°C) in the cooler temperature (-50 to 25°C) range than higher temperature range (-50 to 105°C). Hence, ABS material can be used for temperature range of -50 °C to 105 °C.
vii. ABS is lightweight and vacuum compatible so it may be used for Aerospace industries or space application.

V. Future Scope

Further tests can be performed in order to find the remaining properties of ABS material such as creep, malleability etc. Due to light weight and ease to be metal coated characteristics of ABS material, metal coated ABS can be used for millimetre/ micrometre wave application in Aerospace industries. Metal coated ABS can be tested for thermo-vac condition to analyse it is suited for space application or not.

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